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September 12, 2000

Ms. Magalie Roman Salas
Secretary
Federal Communications Commission
445 12 St., S. W.
Washington, DC 20554

DOCKET FILE COPY ORIGINAL

Re: Interference Modeling and Testing
ET Docket No. 98-153
Ultra Wideband

Dear Ms. Salas:

To understand the impact of Ultra Wideband (UWB) devices on code-division multiple access (CDMA) systems operating in the 1850-1990 MHz Personal Communications Services (PCS) band, Sprint Spectrum, L. P. ("Sprint PCS"), Time Domain, Inc. ("Time Domain"), and Telcordia Technologies ("Telcordia") have been working cooperatively. There are two main components to this work. The first component is based on the mathematical modeling of CDMA PCS handset performance while operating among active UWB transmitters. The second work component is based on laboratory and field testing to verify that the parameters and assumptions used in the modeling work are realistic.

Two documents are attached. The first summarizes the model developed by Telcordia, with substantial consultation with Sprint PCS and Time Domain, to analyze the impact of UWB transmitters on the CDMA PCS forward link. The second summarizes the tests that have been conducted jointly by Sprint PCS and Time Domain to better understand the effect of a UWB transmitter on a PCS handset under controlled conditions. These include laboratory bench tests with conducted RF paths, over-the-air tests in an anechoic (RF absorber-lined) chamber, and field tests at Sprint PCS' test facility.

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List A B C D E

Sprint and Time Domain believe that this work represents a useful contribution to the ongoing industry effort to understand the impact of UWB devices, and hereby jointly submit this material for association with the record of the above-referenced proceeding.

Please direct any questions about this material to either of us.

Respectfully,

Charles W. McKee
Senior Attorney, Sprint PCS
4900 Main Street
Kansas City, MO 64112
(816) 559-2521

cc. Dale N. Hatefield, Chief, Office of Engineering and Technology
Julius P. Knapp, Chief, Policy & Rules Division, OET
John A. Reed, Office of Engineering and Technology

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Time Domain Corporation
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Washington, D.C. 20006

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Please direct any questions about this material to either of us.

Respectfully,

Jeffrey L. Ross

Jeffrey L. Ross
Vice President, Corporate Development & Strategy

ATTACHMENT 1

A Model for Calculating the Effect of UWB Interference on a CDMA PCS System

Dr. Jay Padgett
Senior Research Scientist
Telcordia Technologies
September 12, 2000

Introduction

A model is developed here to provide a mathematical framework for analyzing the impact of ultra wideband (UWB) devices on a code-division multiple access (CDMA) PCS system operating in the 1850-1990 MHz band. The main area of concern is the potential for interference from a UWB transmitter to a nearby PCS handset that is receiving a signal from the PCS forward link. The CDMA forward link has a fixed maximum transmit power, but can control the power allocation (fraction of total forward link power) to each traffic channel as necessary. If a handset experiences increased path loss or interference, the base station can raise its allocation to compensate, up to a limit. If the conditions at the handset require more power than the maximum allowed, then the traffic channel is considered blocked for purposes of this analysis.

If a UWB transmitter is near enough to a PCS handset to affect it, it will either: (1) cause the handset to request additional forward link power to compensate for the interference; or (2) cause the traffic channel to be compromised beyond the ability of the forward link to compensate, due to the power limit, thereby blocking the traffic channel. In the first case, while the traffic channel experiencing the interference can still operate, it is using a larger share of the total forward link capacity.

The exact effect of the UWB transmitter on the PCS handset depends not only on the power received by the PCS handset from the UWB transmitter, but also on the signal strength received from the PCS base station. The power received from the UWB transmitter depends in turn on the UWB transmit power spectral density (PSD) in the PCS band, and the distance between the UWB transmitter and the PCS handset. The purpose of this model is to quantify the blocking probability and the average forward traffic channel power increase due to the UWB interference, under various assumptions about UWB spatial density and distribution, and UWB transmit power spectral density in the PCS band.

Assumptions

1. Free-space loss applies for the path between PCS handset and UWB transmitter. This is appropriate, given the close spacing (several meters or less) required between the UWB transmitter and the PCS handset for any significant impact. The PCS handset and the UWB transmitter antennas are assumed to be aligned with respect to polarization.
2. Up to the limit $\alpha_{\max}$, the forward link will adjust its power allocation just enough to meet the E_b/N_0 requirement. This assumption reflects the power control used in the CDMA forward link.
3. Only the nearest active UWB device affects the PCS handset. With randomly-distributed UWB devices, the interference impact on the handset will be dominated by the nearest active device. Even when active, it is expected that many types of UWB devices will not transmit continuously, but rather transmit bursts or packets as necessary. In that case, it would not be

realistic to sum interference contributions from multiple UWB transmitters, which normally would not all be transmitting simultaneously.

Notation and Constants

W	PCS channel bandwidth (1.2288 MHz)
R	bit rate (14.4 kb/s for rate set 2)
N	PCS handset receiver noise (−105 dBm, assuming an 8-dB noise figure)
F	PCS handset receiver noise figure (8 dB)
N_0	noise power spectral density ($= N/W$)
E_b	received energy per information bit
G_p	processing gain ($\equiv W/R$) (19.4 dB)
$(E_b/N_0)_{\min}$	E_b/N_0 needed for adequate forward traffic channel quality (6.2 dB)
M_J	jamming margin ($\equiv G_p/(E_b/N_0)_{\min} = [(I+N)/C]_{\max}$ (13.2 dB)
α	power allocation as a fraction of total forward link power
$\alpha_{\max}$	the maximum allocation per traffic channel (7.3%)
P_{rx}	total in-cell forward link power received at the handset
Φ_{TXuwb}	transmitted UWB power spectral density in the PCS band
I_{uwb}	received UWB interference power (in band)
I_{uwb1}	interference received by PCS handset from a UWB 1 meter away
F_{no}	forward link non-orthogonality factor, $0 \le F_{no} \le 1$
I_{in}	in-cell interference [$= F_{no}P_{rx}(1-\alpha)$]
d	distance between UWB transmitter and PCS handset (meters)
L_{hs}	additional loss in handset receive path[1]
ρ	density of active UWB transmitters (devices/m^2)

UWB Interference Received at PCS Handset

A useful reference point is the power received by the PCS handset from a UWB device 1 meter away, given by (1). The interference power received from a UWB device some arbitrary distance d away is then given by (2).

dBm	milliwatts	
$I_{uwb1} = \Phi_{TXuwb} + 10\log(W) - L_{hs} - 38$	$I_{uwb1} = \dfrac{\Phi_{TXuwb} W}{L_{hs}} 10^{-3.8}$	(1)
$I_{uwb}(d) = I_{uwb1} - 20\log d$	$I_{uwb}(d) = \dfrac{I_{uwb1}}{d^2}$	(2)

Power Allocation Requirement of PCS Handset

The total received forward link power is P_{rx} and the traffic channel of interest receives a fraction α of that, so the traffic channel power is αP_{rx}. The E_b/N_0 requirement on the traffic channel

[1] Observed to be 7.5 dB in the anechoic chamber tests, for the particular handset used.

requires that $\alpha P_{rx} = (N + I)/M_J$. In-cell interference is $I_{in} = F_{no} P_{rx}(1-\alpha) \cong F_{no} P_{rx}$, where the non-orthogonality factor F_{no} represents the degree to which forward link code orthogonality is compromised (by multipath).[2] Therefore, to meet the E_b/N_0 requirement of the traffic channel, the power allocation must be:

$$\alpha = \frac{1}{M_J}\left(\frac{N}{P_{rx}} + F_{no}\right) \tag{3}$$

If UWB interference is added, then clearly the power allocation must increase by at least

$$\Delta\alpha = \frac{I_{uwb}}{M_J P_{rx}} = \frac{I_{uwb1}}{d^2 M_J P_{rx}} \tag{4}$$

(simply substitute $N + I_{uwb}$ for N in eq. 3) to maintain the E_b/N_0 at its threshold. Otherwise, the call would be unnecessarily dropped.

As discussed in the Annex, outer-cell interference can be approximated as an additional noise term (effectively increasing N), but the impact of outer-cell interference is minimal and can be ignored within buildings (the main area of interest) due to the building penetration loss.

Power Allocation Margin

The available margin in forward power allocation (additional power that can be allocated to overcome interference) is $\Delta_{avail} = \alpha_{\max} - \alpha$. If N (noise) is constant, the minimum power allocation requirement (for $P_{rx} \to \infty$) is $\alpha_{\min} = F_{no}/M_J$. The maximum available margin in forward power allocation without UWB interference therefore is $\Delta_{\max} = \alpha_{\max} - F_{no}/M_J$. The available power allocation margin is the maximum value of $\Delta\alpha$ (given P_{rx}), and determines the amount of UWB interference that can be tolerated without dropping the call, and therefore the minimum distance $d_{\min}$ between the UWB transmitter and the PCS handset. From (4),

$$d_{\min}^2 = \frac{I_{uwb1}}{\Delta_{avail} M_J P_{rx}} \tag{5}$$

A useful parameter is the fraction of the maximum margin that is available (i.e., at a given point in the PCS cell). This is denoted x and defined as:

$$x \equiv \frac{\Delta_{avail}}{\Delta_{\max}} \tag{6}$$

[2] $F_{no} = 0$ corresponds to perfect orthogonality (no in-cell interference), while $F_{no} = 1$ corresponds to no orthogonality (the handset sees the other forward link channels at full power). $F_{no} = 0.5$ represents a 3-dB interference reduction compared to $F_{no} = 1$.

and is related to the received forward link power, from the above definitions and (3), by

$$P_{rx} = \frac{N}{M_J \Delta_{\max}(1-x)}. \tag{7}$$

Combining (5) and (7), with $\Delta_{avail} = x\Delta_{\max}$ gives

$$d_{\min}^2 = \frac{1-x}{x}\frac{I_{uwb1}}{N}. \tag{8}$$

Note that the minimum value of P_{rx} occurs when $x = 0$ (i.e., there is no more forward power allocation margin left, and $\alpha = \alpha_{\max}$). That is,

$$P_{rx\min} = \frac{N}{M_J \Delta_{\max}}. \tag{9}$$

Table 1 shows $P_{rx\min}$ relative to the noise floor, and in dBm for 5-dB and 8-dB noise figures, as a function of F_{no}.

Table 1

F_{no}	$P_{rx\min}/N$ (dB)	$P_{rx\min}$, dBm	
		$F = 8$ dB	$F = 5$ dB
0	−1.8	−106.8	−109.8
0.5	−0.1	−105.1	−108.1
1	+2.9	−102.1	−105.1

The ratio of P_{rx} to $P_{rx\min}$ is related to the corresponding value of x by:

$$\frac{P_{rx}}{P_{rx\min}} = \frac{1}{(1-x)}. \tag{10}$$

<u>Blocking Probability and Average Power Allocation Increase</u>

Given some value of P_{rx} and the corresponding value of $d_{\min}$, the effect of a UWB transmitter will depend on its distance d from the PCS handset. If $d \le d_{\min}$, the forward link cannot deliver enough power to compensate for the interference and the call will be blocked (or dropped, if it is already in progress). If $d > d_{\min}$, the forward link will increase the power allocation to the handset by an amount $\Delta\alpha$, per (4). Given some spatial density ρ of active UWB devices (active UWB devices per m^2), the blocking probability P_b and the average power allocation increase $\langle \Delta\alpha \rangle$ are of interest, where $\langle \cdot \rangle$ denotes the statistical average over variation in the distance d between the UWB transmitter and the PCS handset.

It should be emphasized that it is the density of *active* UWB transmitters that is of interest in determining the effect of the UWB interference. If ρ_{tot} represents the total density of UWB transmitters and p_{active} is the activity duty cycle, or probability that a given UWB transmitter is active, then $\rho = p_{active}\rho_{tot}$. *Active* does not mean that the UWB transmitter is continuously transmitting (or if it is a pulsed system, transmitting a pulse every frame). It means that the device is currently involved in some short-term transaction (e.g., an exchange of packets). The short-term duty cycle should not be factored into the calculation of p_{active}, because it generally does not reduce the effect on the victim PCS handset. For example, suppose that a UWB device is exchanging data with one or more other devices. It transmits a burst, then waits for a response. While active, it may be actually transmitting for 2 milliseconds out of every 20, giving a 10% duty cycle while active. However, a CDMA PCS handset, with its 20-millisecond frame, will experience an average of one interference burst per frame. Thus, the short-term transmit duty cycle does not significantly reduce the interference potential and should not be included in calculation of p_{active}.

Assuming that the effect on the PCS handset is determined by only the nearest active UWB transmitter (that is, power addition from multiple UWB devices is ignored), and the probability density function (pdf) for the distance between the PCS handset and the nearest UWB transmitter is given by $f_d(r)$, then from (4), the average power allocation increase is:

$$\langle \Delta\alpha \rangle = \int_{d_{\min}}^{\infty} \Delta\alpha(r) f_d(r) dr = \frac{I_{uwb1}}{M_J P_{rx}} \int_{d_{\min}}^{\infty} \frac{f_d(r)}{r^2} dr \tag{11}$$

and the blocking probability is

$$P_b = \Pr\{d < d_{\min}\} = \int_{0}^{d_{\min}} f_d(r) dr \ . \tag{12}$$

Different distributions can be used for the distance. One obvious choice is to assume a totally random distribution of UWB devices over area. However, social and physical factors may tend to discourage two people from operating devices in extremely close proximity (e.g., within less than 2-3 feet), which this distribution does not take into account. One possible solution is to simply truncate the uniform distribution below some distance d_0. An alternative to setting a hard lower bound on distance is to use a "smooth" distribution that does not absolutely preclude very close proximity but reduces its likelihood, compared to the uniform distribution. Figure 1 shows the uniform, non-uniform, and truncated uniform (with a cutoff distance of $d_0 = 1$ meter) probability density functions, for a UWB transmitter density of $\rho = 0.1$.

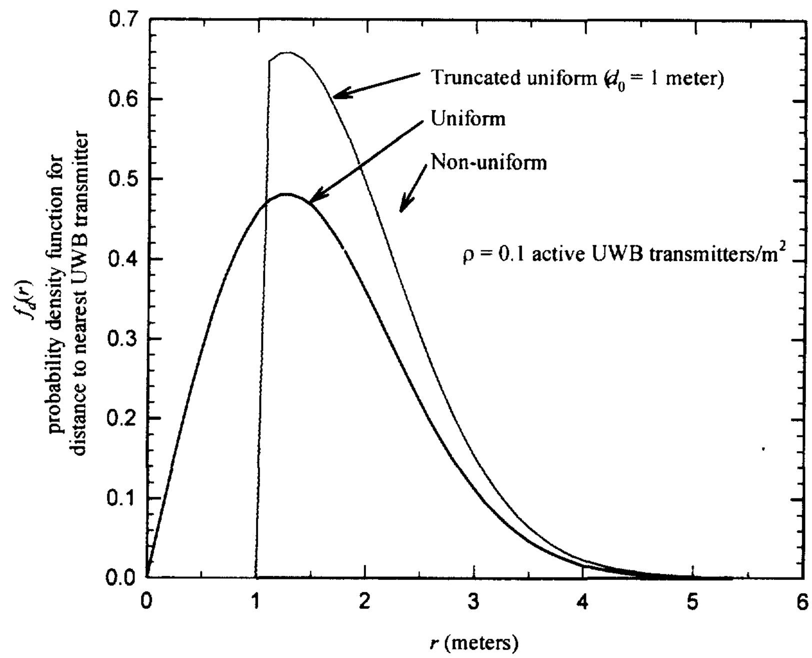

Figure 1: *Probability density functions for minimum UWB to PCS distance*

Table 2 shows the probability density functions (pdfs) used for these three cases, and the resulting expressions for $\langle \Delta\alpha \rangle$ and P_b, from (11) and (12) where $u_{\min} = \pi\rho d_{\min}^2$, $u_0 = \pi\rho d_0^2$, $k = \pi\rho I_{uwb1}/M_J P_{rx}$, and $E_1(x) = \int_x^\infty \frac{e^{-t}}{t} dt, (x > 0)$ is the first-order exponential integral, shown in Figure 2. Physically, $u = \pi\rho d^2$ represents the *average* number of active UWB transmitters within a radius d of the PCS handset.

Table 2: *Average power allocation increase and blocking probability for three different distance distributions.*

	pdf $f_d(r)$	$\langle \Delta\alpha \rangle$	P_b
uniform	$2r\rho\pi e^{-\rho\pi r^2}$	$kE_1(u_{\min})$	$1 - e^{-u_{\min}}$
truncated uniform	$2r\rho\pi e^{-\rho\pi(r^2 - d_0^2)}$ $d > d_0$ 0 $d \le d_0$	$ke^{u_0}E_1(u_{\min})$ $u_{\min} > u_0$ $ke^{u_0}E_1(u_0)$ $u_{\min} \le u_0$	$1 - e^{-u_{\min}}e^{u_0}$ $u_{\min} > u_0$ 0 $u_{\min} \le u_0$
non-uniform	$2(\rho\pi)^2 r^3 e^{-\rho\pi r^2}$	$ke^{-u_{\min}}$	$1 - e^{-u_{\min}}(1 + u_{\min})$

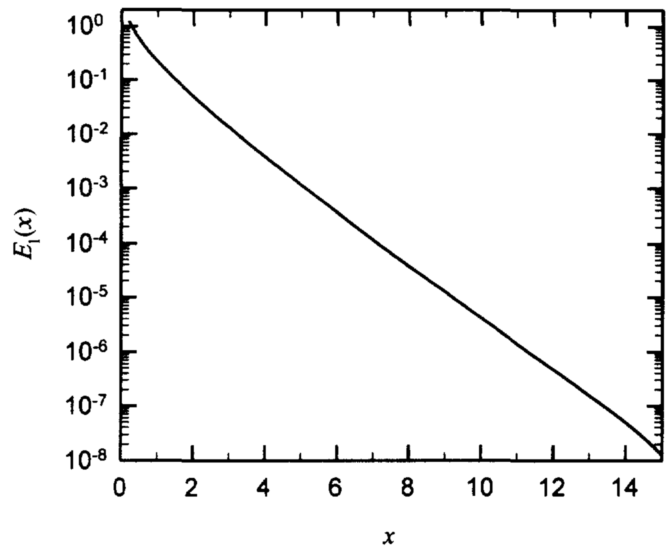

Figure 2: *The first-order exponential integral.*

Interference Mitigation Objectives and Tradeoffs

Note that $\langle \Delta\alpha \rangle$ and P_b depend on two parameters: k and $u_{\min}$ (and in the case of the truncated uniform distribution, also u_0). It is useful to express k and $u_{\min}$ in several different forms as shown in Table 3, using (5)-(8).

Table 3: *Different expressions for k and $u_{\min}$.*

k	$u_{\min}$
$\pi\rho \dfrac{I_{uwb1}}{M_J P_{rx}}$	$\pi\rho \dfrac{I_{uwb1}}{x\Delta_{\max} M_J P_{rx}}$
$\pi\rho \dfrac{I_{uwb1}}{N} \Delta_{\max}(1-x)$	$\pi\rho \dfrac{I_{uwb1}}{N} \dfrac{(1-x)}{x}$
$\pi\rho \dfrac{I_{uwb1}}{N} \Delta_{\max} \dfrac{P_{rx\min}}{P_{rx}}$	$\pi\rho \dfrac{I_{uwb1}}{N} \dfrac{1}{P_{rx}/P_{rx\min} - 1}$
$x\Delta_{\max} u_{\min}$	$\dfrac{k}{x\Delta_{\max}}$

From the third row, it is clear that given $\Delta_{\max}$, which depends on F_{no}, $\langle \Delta\alpha \rangle$ and P_b depend on three factors: (1) the UWB density ρ; (2) the ratio I_{uwb1}/N; and (3) $P_{rx}/P_{rx\min}$, the ratio of the received forward link P_{rx} power to the minimum value of P_{rx} for which a traffic channel can be maintained in the absence of interference.

UWB Transmit PSD vs. d_{min} and Received Forward Link Power

One potential approach to finding acceptable interference levels is to determine, for a given ρ and $P_{rx}/P_{rx\min}$, the value of I_{uwb1}/N that gives some desired values of $\langle \Delta\alpha \rangle$ and P_b. The result depends on the target values of ρ, $P_{rx}/P_{rx\min}$, $\langle\Delta\alpha\rangle$, and P_b, and the distance distribution used for the calculations. A simpler approach is to initially focus on an objective for $d_{\min}$ and the received forward link power level at which that objective must be met. Combining (7)-(9), yields:

$$\frac{I_{uwb1}}{N} = d_{\min}^2\left(\frac{P_{rx}}{P_{rx\min}} - 1\right), \qquad (13)$$

The parameter I_{uwb1}/N can be translated to the power spectral density (PSD) transmitted by the UWB device using

$$\frac{I_{uwb1}}{N}(\text{dB}) = \Phi_{TXuwb}(\text{dBm/MHz}) - 38 - L_{hs} - N_0 \qquad (14)$$

where Φ_{TXuwb} is the effective isotropic PSD (dBm/MHz) radiated by the UWB device, 38 dB is the 1-meter free-space path loss at the frequency of interest, L_{hs} is the additional front-end loss in the handset (assumed 7.5 dB here), and N_0 is the PSD of the receiver front-end noise in dBm/MHz, which is $-114 + F$, where F is the handset receiver noise figure, assumed 8 dB here. With these values,

$$\Phi_{TXuwb} = \frac{I_{uwb1}}{N} - 60.5 \quad (\text{dBm/MHz}). \qquad (15)$$

Combining (13) and (15) gives the family of curves shown in Figure 3. The level suggested in the Notice of Proposed Rule Making (NPRM) for frequencies below 2 GHz is 12 dB below the current FCC limit for unintentional radiators (500μV/m at 3m measured with a 1-MHz bandwidth), which equates to –41.2 dBm/MHz), or –53.2 dBm/MHz. This level is shown as the dotted line in Fig. 3. The other reference levels shown are intended to account for a potential *de facto* derating of the power due to a reflection from the ground plane, which can cause positive reinforcement and raise the received signal nearly 6 dB above what it would be with a direct ray only.[3] In addition, there may be 1-2 dB of margin allowed for uncertainties in equipment calibration, cable loss, etc. Hence, limits of –41.2 and –53.2 dBm/MHz on the measured signal may correspond to effective limits on the order of –48 and –60 dBm/MHz, respectively, for the actual equivalent isotropic transmitted power spectral density. The secondary reference lines therefore are shown at –48 and –60 dBm/MHz.

Clearly, the relationship between the actual radiated PSD and the limit will depend on the details of the measurement procedure. The effect of any particular limit cannot be considered independent of the test used to determine compliance. The impact analysis must focus on the actual radiated PSD, and then relate that to a compliance limit, given the test procedure.

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[3] While a ground plane is not strictly required for measurements above 1 GHz (see ANSI C63.4-1992, section 8.2.4), most test sites do include a reflective ground plane. Even with a ground plane, the effect of the ground reflection will depend on the directivity of the measurement antenna, which may attenuate the ground reflection and reduce the effect of the positive reinforcement.

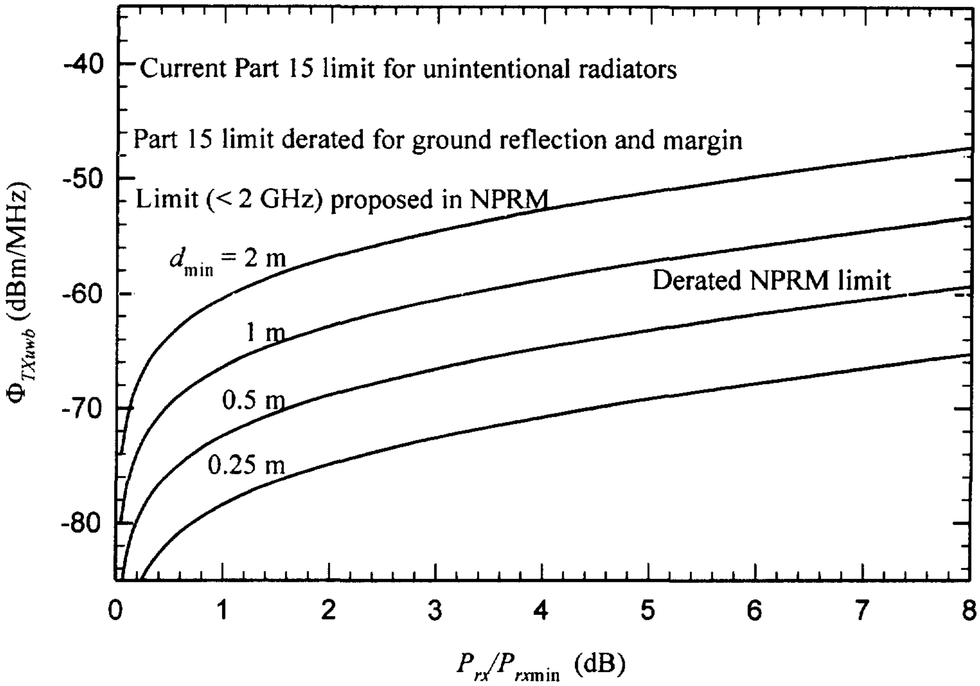

Figure 3

The result in Figure 3 does not depend on the density ρ, nor does it depend on the assumed distance distribution. It is also general, in that it applies to any value of F_{no}. As would be expected, as $P_{rx} \rightarrow P_{rx\min}$, $\Phi_{TXuwb} \rightarrow 0$, or $-\infty$ dB, because the margin is exhausted.

Note also that the curves in Figure 3 depend only on assumption 1 (free space path loss between the UWB transmitter and the PCS handset). The other assumptions, and the assumed distance distribution (including the UWB density), only become involved when calculating $\langle \Delta\alpha \rangle$ and P_b.

If the environment in which the PCS handset is operating includes some external ambient noise N_{ext}, its effect can easily be included in the model by substituting $N_{ext} + N$ for N in all equations. As an example, assume that N_{ext} is 12 dB above thermal (kTB) noise,[4] as measured with an ideal lossless dipole. The noise into the handset receiver is then 4.5 dB above thermal (accounting for the 7.5 dB handset front-end loss), which is 3.5 dB below the device noise of the handset receiver, assuming an 8-dB noise figure. In that case, $N_{ext} + N$ is about 9.6 dB above the thermal level, giving an effective increase of 1.6 dB. Ambient noise will depend on the particular environment, and can vary widely. Complete characterization of ambient noise is beyond the scope of this paper, but any given level can easily be incorporated into calculations using the model.

[4] k is Boltzman's constant (1.38×10^{-23} watts/Hz/°K), T is the ambient temperature in °K (normally taken as 290° K), and B is the bandwidth in Hz. Thus, the baseline thermal noise PSD is –174 dBm/Hz.

Blocking Probability
From (13),

$$u_{\min} = \pi\rho \frac{I_{uwb1}}{N} \frac{1}{P_{rx}/P_{rx\min} - 1} \tag{16}$$

and from Table 2, the blocking probability is a function of $u_{\min}$. Thus, for a given value of $P_{rx}/P_{rx\min}$, blocking probability depends on $\rho(I_{uwb1}/N)$ as shown in Figures 4 and 5 for the uniform and non-uniform distance distributions, respectively.

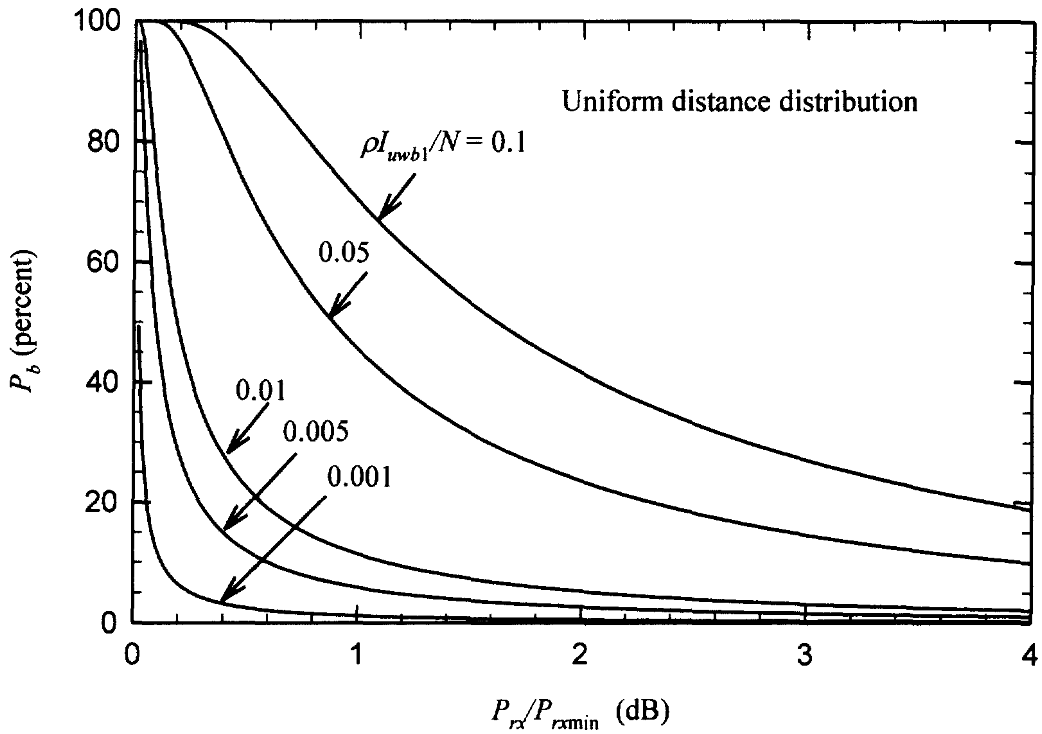

Figure 4

From (15), $I_{uwb1}/N = 1$ (0 dB) corresponds to $\Phi_{TXuwb} = -60.5$ dBm/MHz, and ρ represents the average number of active UWB devices per square meter. As an example, therefore, $\rho I_{uwb1}/N = 0.01$ corresponds to an average of 1 active UWB transmitter, radiating –60.5 dBm/MHz in the PCS band, every 100 m^2, or roughly every 1000 square feet. To carry the example further, this equates to an average of 2 active UWB devices in a 2000 square foot house. Obviously, the average density of active UWB devices will be highly dependent on the environment (e.g., home, office, common public space, etc.).

Curves are shown for both the uniform and non-uniform distribution in an attempt to bound the problem. For relatively high densities (e.g., $\rho = 0.1$), the non-uniform distribution is probably a better representation of reality, because it reflects the fact that users will tend not to be operate in extremely close proximity. With very low densities (e.g., $\rho = 0.005$), the uniform distribution may be reasonably accurate. For intermediate densities it seems reasonable to expect that the blocking probability will lie between the uniform and non-uniform distribution curves.

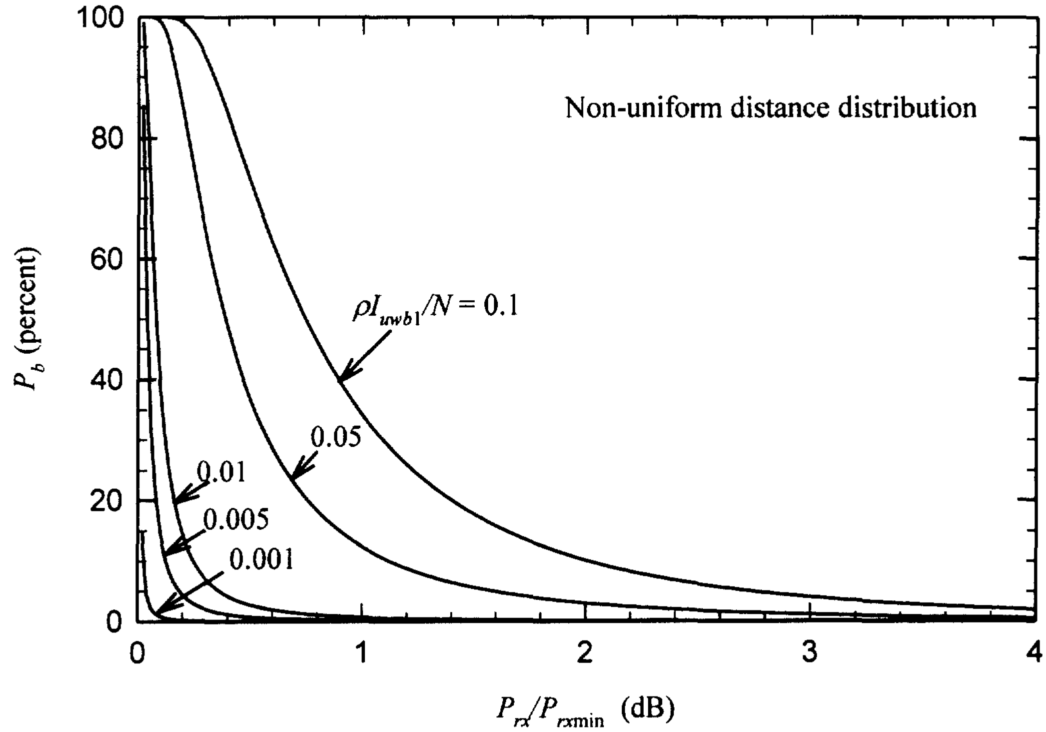

Figure 5

The main point of Figs. 4 and 5 is that if $\rho(I_{uwb1}/N)$ is small enough, the significant blocking levels are confined to a very narrow range of P_{rx}.

An objective for I_{uwb1}/N can be formulated in terms of some target blocking probability P_0 and some target value $P_{rx0}/P_{\min}$. If $P_b << 1$, then $u_{\min} << 1$ and $e^{-u_{\min}} \cong 1 - u_{\min}$. Hence, assuming the objective blocking probability is small ($P_0 << 1$), then $u_{\min} \cong P_0$ for the uniform distribution and $u_{\min} \cong \sqrt{P_0}$ for the non-uniform distribution. Accordingly,

$$\frac{I_{uwb1}}{N} = \frac{P_0}{\pi\rho}\left(\frac{P_{rx}}{P_{rx\min}} - 1\right) \qquad \text{uniform} \tag{17}$$

$$\frac{I_{uwb1}}{N} = \frac{\sqrt{P_0}}{\pi\rho}\left(\frac{P_{rx}}{P_{rx\min}} - 1\right) \qquad \text{non-uniform} \tag{18}$$

Power Allocation Increase and Blocking Probability vs. Received Power

Figures 6-9 show $\langle \Delta\alpha \rangle$ and P_b per Table 2, for different combinations of distance distribution (uniform or non-uniform), transmitted UWB PSD (Φ_{TXuwb}), in dBm/MHz, and UWB density ρ.

An 8-dB noise figure has been assumed. Note that $\langle \alpha \rangle$ is shown on the left-hand vertical axis, and P_b on the right.

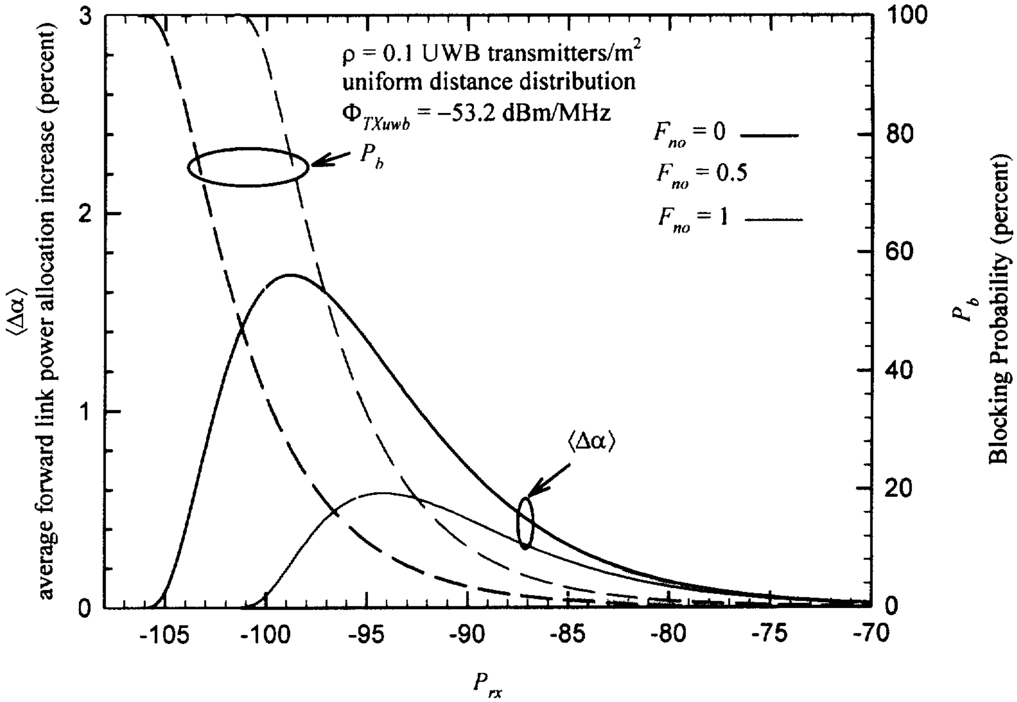

Figure 6

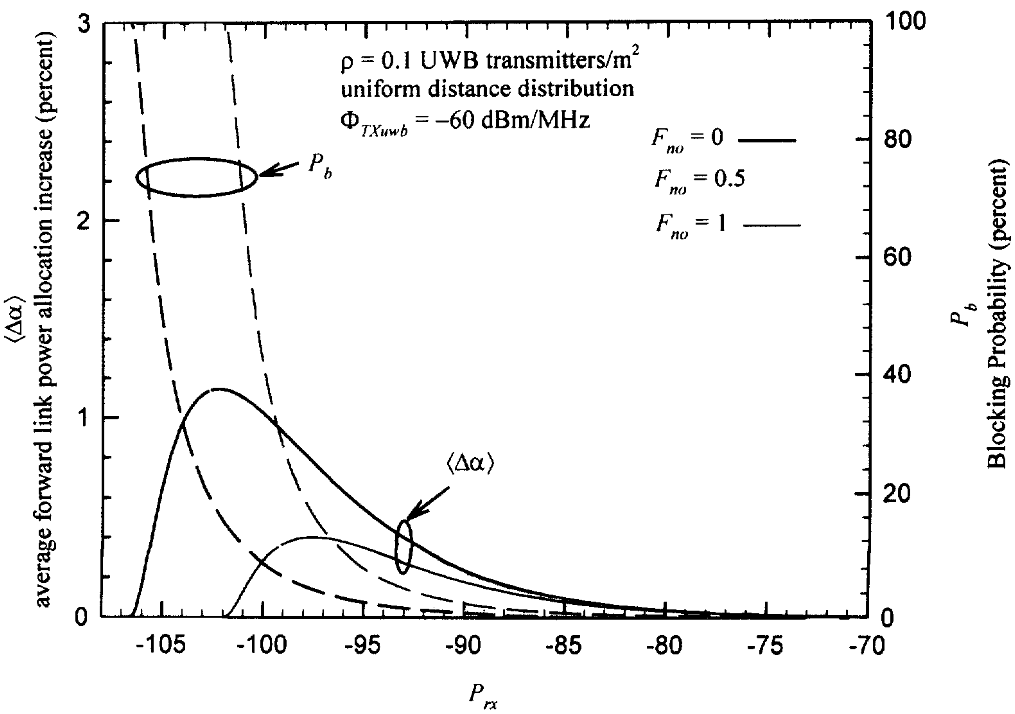

Figure 7

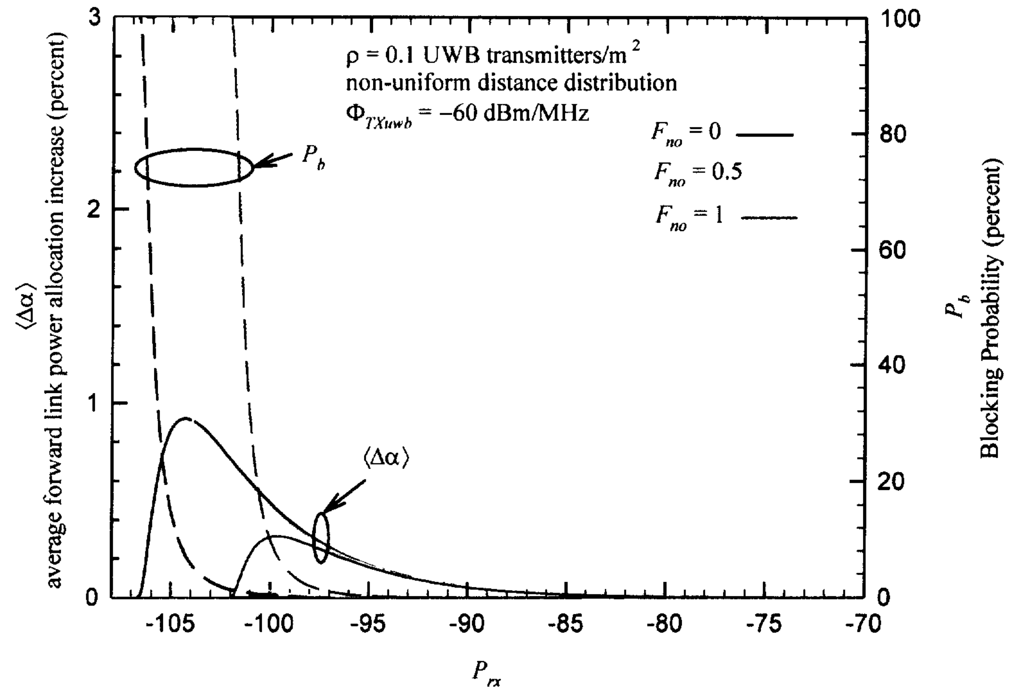

Figure 8

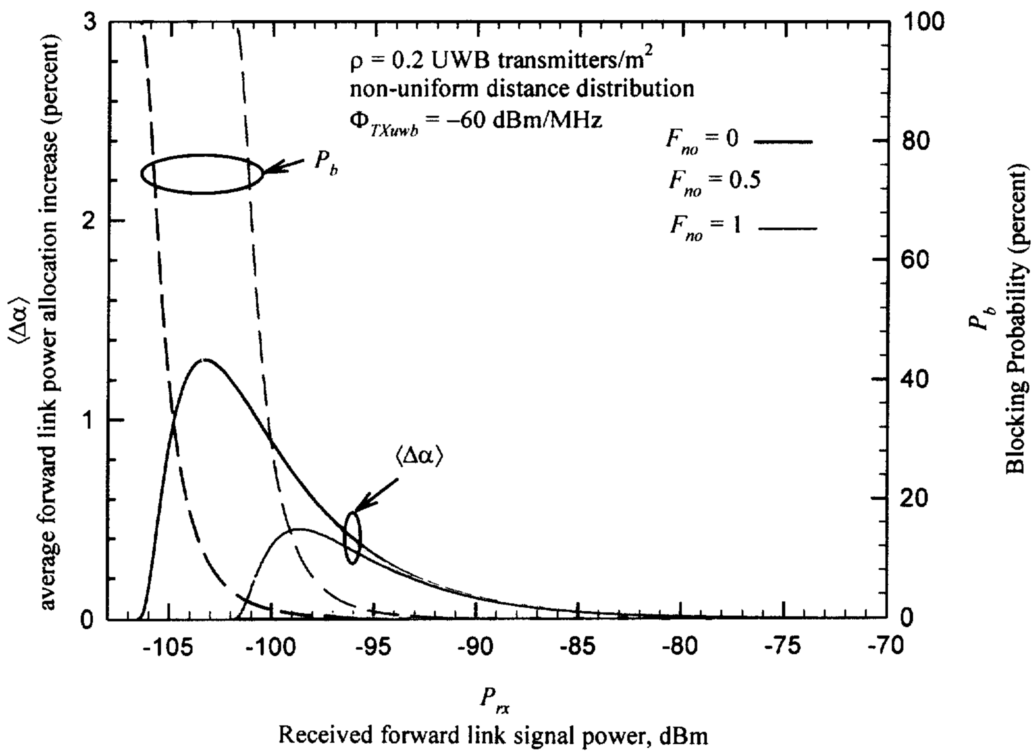

Figure 9

In these graphs, $\langle \Delta\alpha \rangle$ is computed according to (11), and the average is taken only over the portion of the distance distribution for which the handset is not blocked (that is, $d \geq d_{\min}$). Therefore, $\langle \Delta\alpha \rangle / (1 - P_b)$ represents the average power allocation increase for handsets that are not blocked. In fact, the handsets that are blocked, assuming their calls are dropped, actually contribute to a reduction in the total power allocation. The average net change in the power allocation is:

$$\langle \Delta\alpha \rangle_{net} = \langle \Delta\alpha \rangle - \alpha P_b . \tag{19}$$

Figure 10 shows $\langle \Delta\alpha \rangle_{net}$ instead of $\langle \Delta\alpha \rangle$ but otherwise is the same as Figure 8. Note that when the blocking probability becomes large, $\langle \Delta\alpha \rangle_{net}$ goes sharply negative, as would be expected.

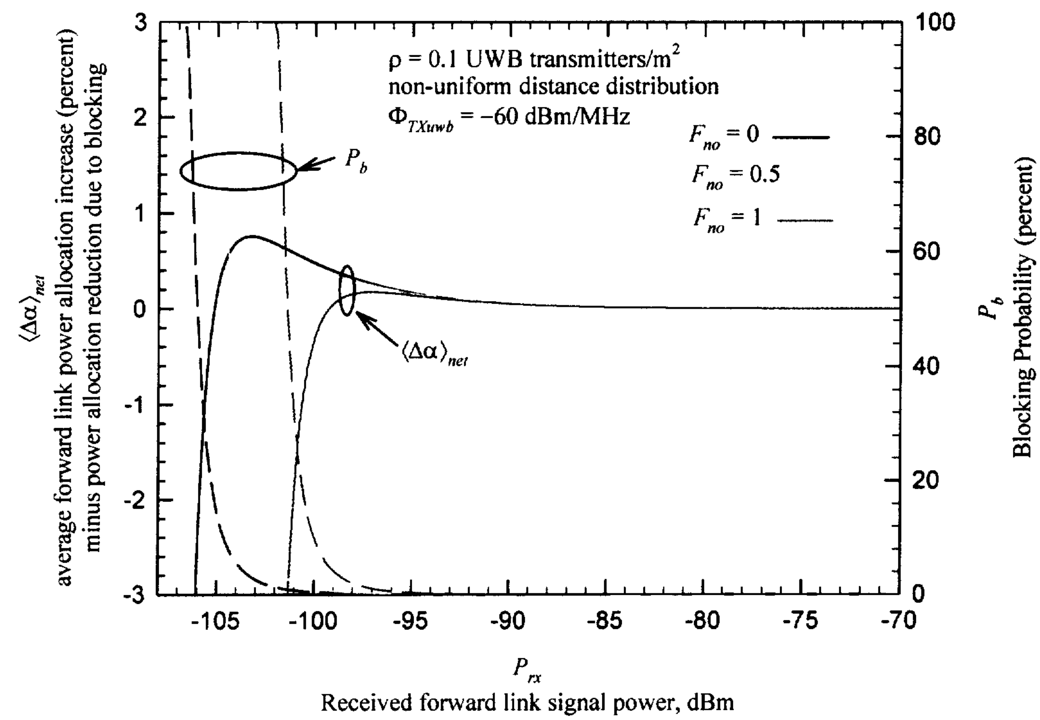

Figure 10

Impact Averaged Over Cell Area

The blocking probability and the average change in the forward link power allocation have been shown as functions of the received forward link power, which depends on the location of the handset relative to the cell site, and on building loss. The most severe impact is confined to signal levels near the minimum ($P_{rx\min}$). Clearly, one potential measure of UWB interference impact is the blocking probability at a received signal level that is some X dB above $P_{rx\min}$, given some value of ρ. Given the distance distribution, this criterion actually reduces to a requirement on $d_{\min}$ vs. $P_{rx}/P_{rx\min}$ (Fig. 3). Another conceivable measure is the blocking probability (or power allocation impact) averaged over the entire cell. To explore this possibility, this section develops expressions for the blocking probability and the change in the power allocation, averaged over the cell.

Given a distance d between the UWB transmitter and the PCS handset, the required forward link power allocation is

$$\alpha = \frac{F_{no}}{M_J} + \frac{1}{M_J P_{rx}}\left(N + \frac{I_{uwb1}}{d^2}\right) = \frac{F_{no}}{M_J} + \frac{N}{M_J P_{rx\min}} \frac{P_{rx\min}}{P_{rx}}\left(1 + \frac{I_{uwb1}/N}{d^2}\right) \tag{20}$$

With $F_{no}/M_J = \alpha_{\min}$, and from (9) in the model summary, $N/M_J P_{rx\min} = \Delta_{\max}$, so (20) becomes:

$$\alpha = \alpha_{\min} + \Delta_{\max} \frac{P_{rx\min}}{P_{rx}}\left(1 + \frac{I_{uwb1}/N}{d^2}\right) \tag{21}$$

Let r_c be the cell radius (corresponding to a received power level of $P_{rx\min}$), and d_c be the distance of the handset from the cell center (corresponding to a received power level of P_{rx}). Then, defining $s \equiv d_c/r_c$:

$$\frac{P_{rx\min}}{P_{rx}} = s^{\gamma} \tag{22}$$

where γ is the path loss exponent, generally between 3 and 4.

Since $\alpha_{\max} = \alpha_{\min} + \Delta_{\max}$, it is clear that for a given value of d, $\frac{P_{rx\min}}{P_{rx}} < \left(1 + \frac{I_{uwb1}/N}{d^2}\right)^{-1}$ must be satisfied to avoid blocking. Hence, the maximum value of s for which the traffic channel can be maintained under interference-free conditions is

$$s_{\max} = \left(1 + \frac{I_{uwb1}/N}{d^2}\right)^{-1/\gamma}, \tag{23}$$

and the required power allocation can be expressed as

$$\begin{aligned} \alpha &= \alpha_{\min} + \Delta_{\max} s^{\gamma} s_{\max}^{-\gamma} && s \le s_{\max} \\ &= 0 && s > s_{\max} \end{aligned}. \tag{24}$$

If PCS handsets are uniformly-distributed throughout the cell sector, then the probability density function (pdf) of s is:

$$f_s(\xi) = 2\xi \qquad 0 \le \xi \le 1 \tag{25}$$

and the power allocation averaged over the cell sector, given that each PCS handset has a UWB transmitter d meters away[5], is

$$\overline{\alpha}_{w/uwb} = \int_0^{s_{\max}} \left(\alpha_{\min} + \Delta_{\max} s^{\gamma} s_{\max}^{-\gamma}\right) \cdot 2s\, ds = s_{\max}^2 \left(\alpha_{\min} + \frac{\Delta_{\max}}{\gamma/2+1}\right), \tag{26}$$

where the overbar indicates an average over cell area. Without the UWB transmitters, the average power allocation requirement over the cell is:

$$\overline{\alpha}_{nouwb} = \int_0^{1} \left(\alpha_{\min} + \Delta_{\max} s^{\gamma}\right) \cdot 2s\, ds = \alpha_{\min} + \frac{\Delta_{\max}}{\gamma/2+1}. \tag{27}$$

The blocking probability in this case is the probability that, given the distance d, the forward link power (P_{rx}) is inadequate to overcome the UWB interference with the maximum power allocation $\alpha_{\max}$. This is:

$$P_{b|d} = \Pr\{s > s_{\max}\} = 1 - s_{\max}^2. \tag{28}$$

Note that

$$\overline{\alpha}_{w/uwb} = \left(1 - P_{b|d}\right)\overline{\alpha}_{nouwb} \tag{29}$$

Therefore,

$$\overline{\Delta\alpha} = -P_{b|d}\,\overline{\alpha}_{nouwb} \tag{30}$$

The key point here is that for any distance d between the UWB transmitter and the PCS handset, <u>the cell-average power allocation per handset is less than it is without the interference from the UWB devices, due to the blocking</u>. Moreover, the average power per non-blocked handset is the same as the average power per handset without the UWB devices; that is,

$$\overline{\alpha}_{nb} = \frac{\overline{\alpha}_{w/uwb}}{\left(1 - P_{b|d}\right)} = \overline{\alpha}_{nouwb} = \alpha_{\min} + \frac{\Delta_{\max}}{\gamma/2+1}. \tag{31}$$

This is because, in effect, the presence of the UWB interference has redefined the cell edge, effectively increasing N.

This is a significant result, because the average power increase per non-blocked handset is <u>independent of d</u>. Therefore, it is the same regardless of the pdf assumed for d (e.g., uniform, non-uniform, etc.). Moreover, the net power allocation change, averaged over the cell area, will always be negative (less forward link power is used) independent of the distribution of d.

[5] Clearly, this is a idealized assumption, but is useful for illustrative purposes.

As an example of applying the method described above, Figures 11 and 12 show $\overline{\alpha}_{w/uwb}$ and $P_{b|d}$, respectively, for the specific condition of $\gamma = 3.5$ and $F_{no} = 0.5$, and Table 1 gives $\overline{\alpha}_{nouwb}$ for different combinations of γ and F_{no}.

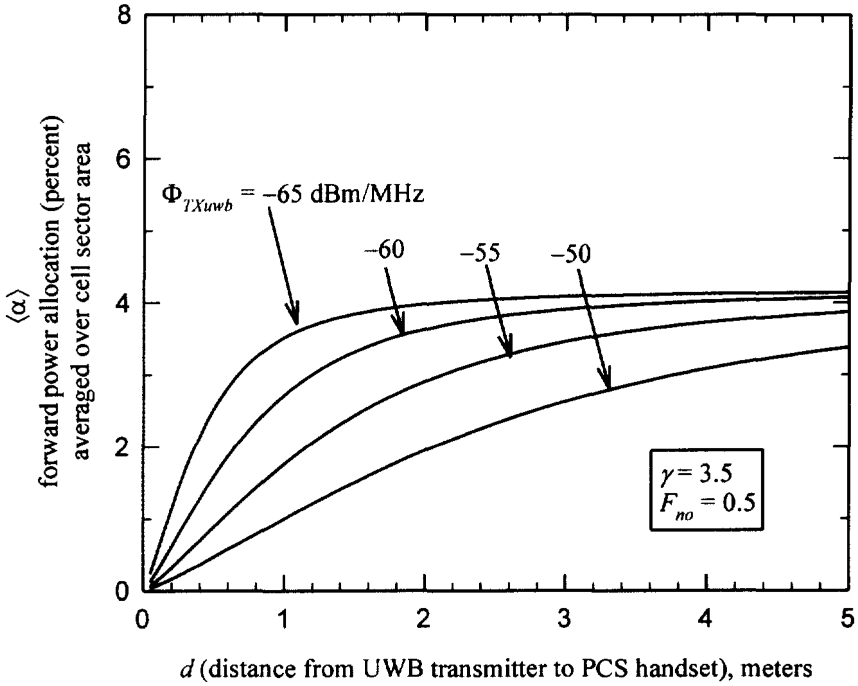

Figure 11

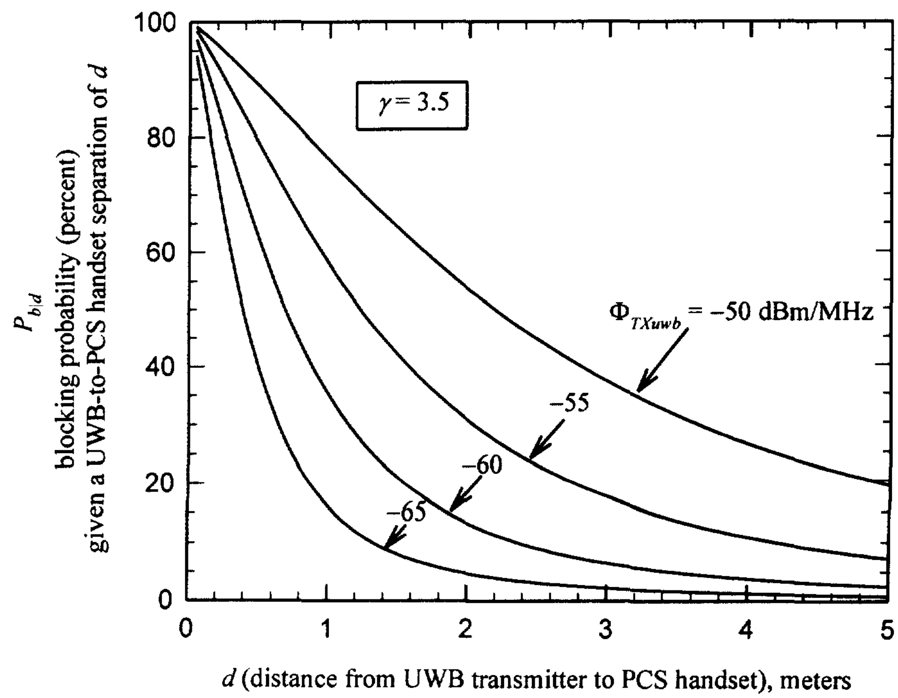

Figure 12

Table 4: *Required forward link power allocation, averaged over sector area ($\overline{\alpha}_{no\,uwb}$).*

F_{no}	$\gamma = 3$	$\gamma = 3.5$	$\gamma = 4$
0	2.9%	2.6%	2.4%
0.5	4.4%	4.2%	4.0%
1	5.8%	5.7%	5.6%

Note in Fig. 11 that as $d \to \infty$, $\overline{\alpha}_{w/uwb} \to \overline{\alpha}_{no\,uwb}$ as would be expected.

Now suppose that only some fraction p_{active} of the UWB devices are actually transmitting. In that case, the blocking probability becomes $p_{active}\left(1 - s_{\max}^2\right)$, and

$$\alpha_{w/uwb} = \left[1 - p_{active}\left(1 - s_{\max}^2\right)\right]\overline{\alpha}_{no\,uwb} \tag{32}$$

Now consider J different distances $d_1, d_2, \ldots d_J$, each with an associated activity probability $p_1, p_2, \ldots p_J$, where p_j represents the probability that for a handset, the nearest active UWB device will be d_j meters away. Clearly, this requires that $\sum_{j=1}^{J} p_j \le 1$. In this case, the average blocking probability becomes

$$\overline{P_b} = \sum_{j=1}^{J} p_j \left[1 - s_{\max}^2\left(d_j\right)\right] \tag{33}$$

As $J \to \infty$ the distribution of the $\{p_j$ approaches a pdf, and

$$\overline{P_b} = \int_0^\infty f_d(r)\left[1 - s_{\max}^2(r)\right]dr\,. \tag{34}$$

Averages over Cell Area and UWB-to-Handset Distance

A single set of impact metrics can be calculated by averaging P_b and $\langle \Delta\alpha \rangle_{net}$ over cell area:

$$\overline{\langle \Delta\alpha \rangle}_{net} = \int_0^1 \left(\langle \Delta\alpha(s) \rangle - P_b(s)\alpha_0(s)\right) \cdot 2s\,ds \tag{35}$$

$$\overline{P_b} = \int_0^1 P_b(s) \cdot 2s ds \tag{36}$$

where as before, $\langle \cdot \rangle$ represents an average over the distribution of d (UWB transmitter-to-PCS handset distance) Thus, $\overline{\langle \cdot \rangle}$ is the average over both d and cell area.

From Table 3:

$$P_b = \begin{cases} 1 - e^{-u_{\min}} & \text{uniform} \\ 1 - (1 + u_{\min})e^{-u_{\min}} & \text{non-uniform} \end{cases} \tag{37}$$

$$\langle \Delta\alpha \rangle = \begin{cases} kE_1(u_{\min}) & \text{uniform} \\ ke^{-u_{\min}} & \text{non-uniform} \end{cases} \tag{38}$$

with k, $u_{\min}$, and α_0 as functions of s given by:

$$k = \pi\rho \frac{I_{uwb1}}{N} \Delta_{\max} s^{\gamma} \tag{39}$$

$$u_{\min} = \pi\rho \frac{I_{uwb1}}{N} \frac{1}{s^{-\gamma} - 1} \tag{40}$$

$$\alpha_0 = \alpha_{\min} + \Delta_{\max} s^{\gamma} \tag{41}$$

Figs. 13 and 14 show $\overline{\langle \Delta\alpha \rangle}_{net}$ for the uniform and non-uniform distance distribution, and Figs. 15 and 16 show $\overline{P_b}$ for the same two cases. The integration in (35) and (36) was performed numerically.

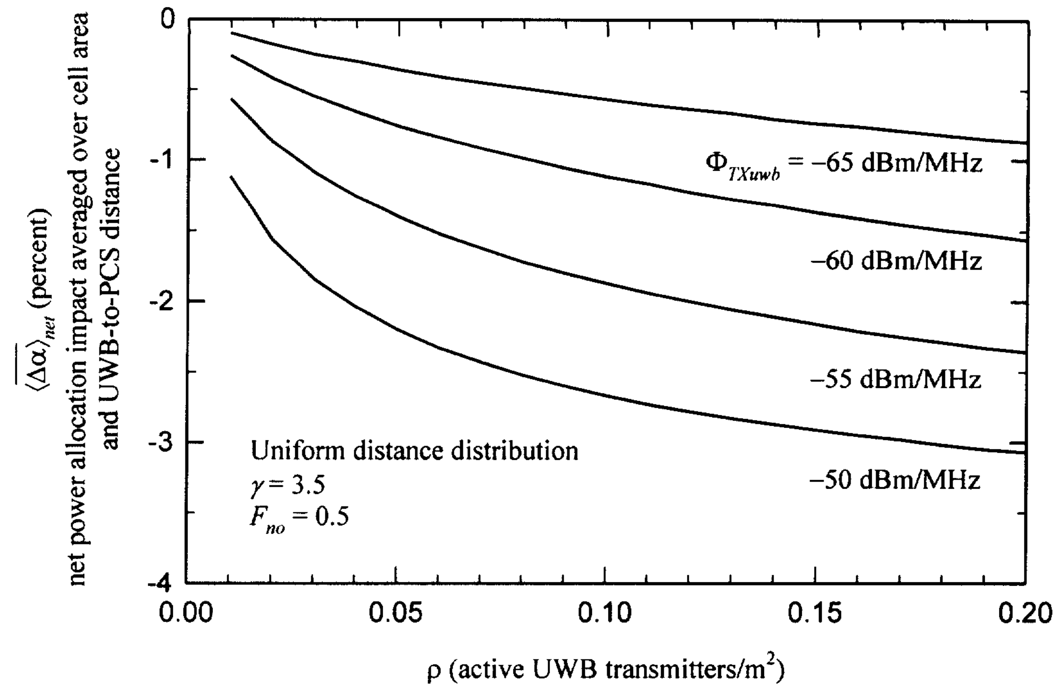

Figure 13

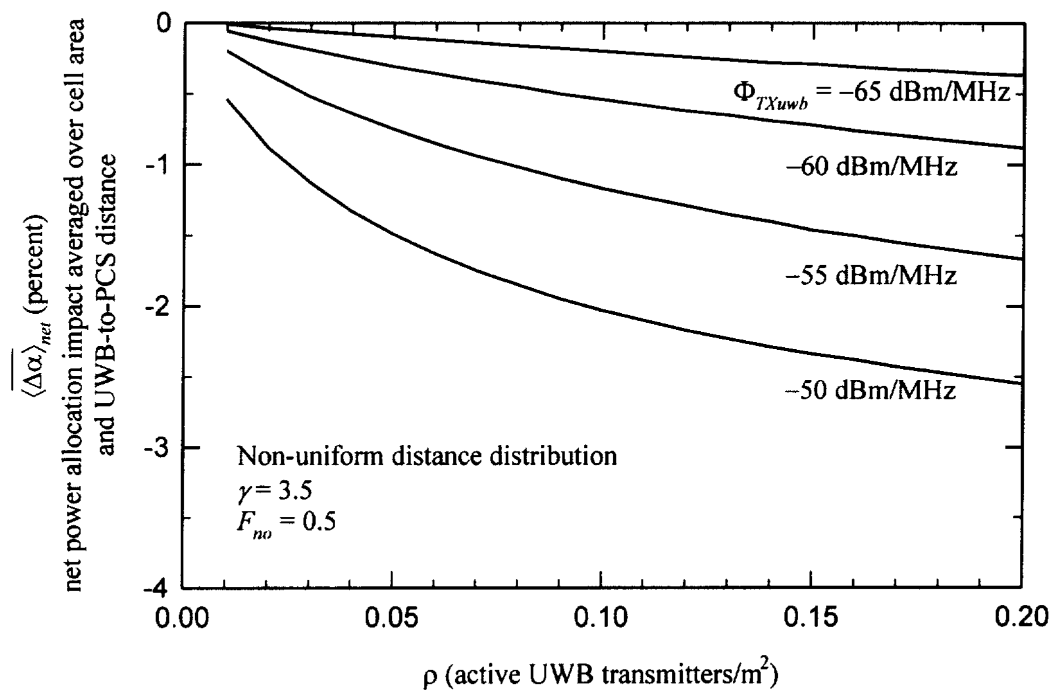

Figure 14

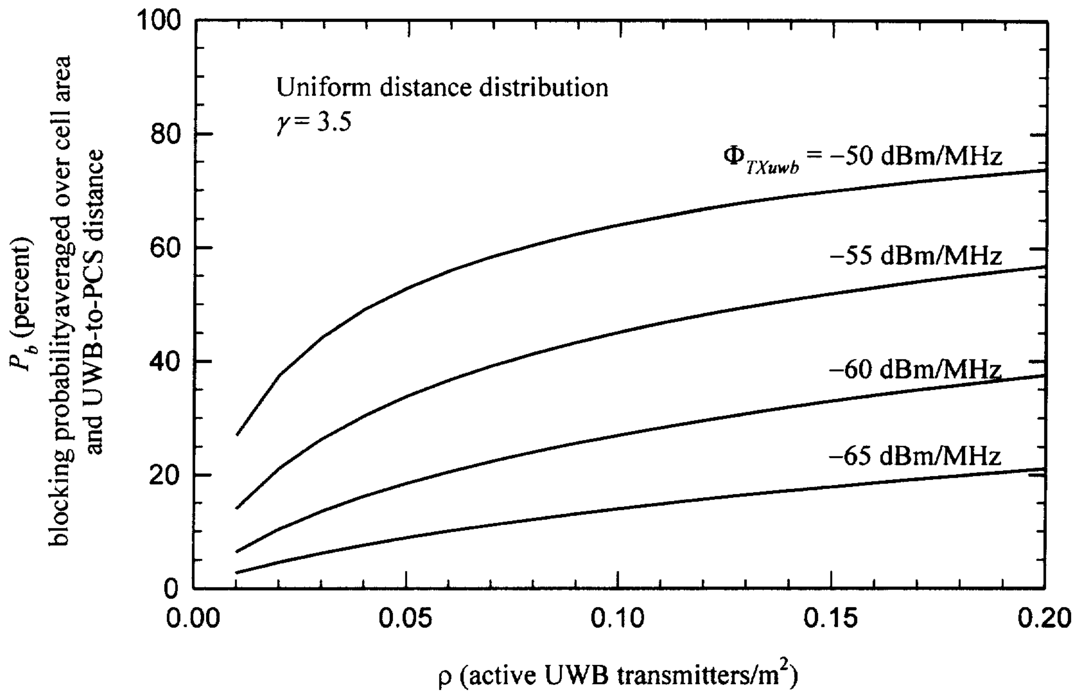

Figure 15

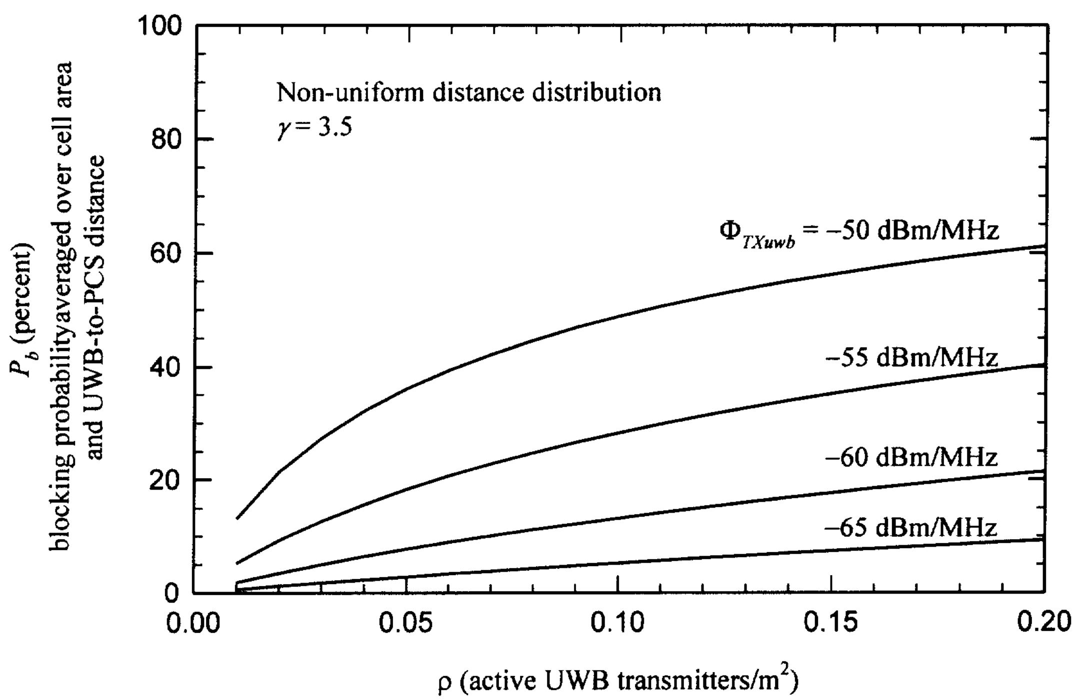

Figure 16

Concluding Remarks

This model provides the means to quantify tradeoffs between UWB transmit power spectral density, impact on the PCS handsets (blocking and power increase), UWB spatial density, and received forward link power. The assumptions and parameters used have been explicitly stated.

It is worth emphasizing that the path loss (1) includes a 7.5-dB loss in the handset receive path, based on the anechoic chamber measurement; and (2) does not include the effects of random handset and UWB orientation, which can affect the path loss. However, the model is described mathematically in sufficient detail to allow interested parties to explore the effects of other sets of parameters and assumptions.

Interference to a PCS handset from a nearby UWB transmitter can have one of two effects: (1) it can cause the forward link to allocate more power to the traffic channel assigned to the handset, to compensate for the interference; or (2) if the maximum allowable power allocation is inadequate to compensate for the interference, the traffic channel will be dropped or blocked. The extent of the required power allocation increase to compensate for the interference will depend on the total forward link power received by the handset from its PCS base station, the power spectral density (PSD) radiated by the UWB transmitter within the PCS band, and the distance between the handset and the UWB transmitter. The model developed here quantifies the relationship among these factors. It also provides calculations of the average forward link power increase and the blocking probability, given the average spatial density of active UWB devices and the transmitted PSD.

The UWB interference actually causes a *reduction* in the total forward link power allocation averaged over the cell or cell sector. This is because some handsets are blocked by the interference, and therefore draw no forward link power. The net change in forward link power allocation due to UWB interference therefore does not seem to be a good direct measure of interference impact. Metrics based on the blocking probability appear to be more useful indicators of impact (although it is clear from eq. 30 that the cell-average power allocation decrease is linearly-related to the cell-average blocking probability).

The purpose of this model is to help determine an acceptable transmit PSD level for UWB devices in the PCS band. It should be kept in mind that UWB transmit PSD, as used here, corresponds to the effective isotropic radiated PSD of the UWB device. To determine the corresponding regulatory limit, the test procedure must be considered. Testing on a standard 3-meter site (with a ground plane) may introduce reflections that could increase the measured field strength above the comparable free-space value. In addition, the settings of the measuring instrument (e.g., a spectrum analyzer) could introduce a bias in the measured result. When measured with a conventional bandwidth such as 1 MHz, the UWB signal may appear noise-like, with a significant peak-to-average ratio (e.g., 8-10 dB). To measure the actual PSD, a true power average must be measured. Averaging decibel values will introduce a negative bias (2.5 dB for dBm vs. milliwatts with Gaussian noise), while using peak detection or "max hold" settings can introduce a positive bias. These factors must be taken into account in translating a measured result to the true power-average isotropic radiated PSD.